SHORELINE RESPONSE TO BREAKWATERS WITH TIME-DEPENDENT WAVE TRANSMISSION

Ty V. Wamsley[1], Nicholas C. Kraus[1], and Hans Hanson[2]

Abstract: Wave transmission is a leading parameter determining the response of the shoreline to a detached breakwater, reef, or spur attached to a jetty. To improve the predictive capability of the shoreline response numerical model GENESIS, published empirical formulas for the wave transmission coefficient were incorporated to calculate time-dependent wave transmission and shoreline response. Simulations for different structural configurations, wave climates, and water levels demonstrate the functional utility of time-dependent wave transmission on shoreline response predictions. Results indicate that variable wave transmission is of significance for modeling the response of the beach to submerged and emergent near-surface structures. Predictions of the model are examined in application to a functional design of a submerged spur being studied as a possible sediment-control measure for the north jetty at Grays Harbor, WA. Results show that for design applications, beach response under time-varying forcing cannot be anticipated with a constant transmission coefficient. The improved capability is expected to have wide applicability.

INTRODUCTION

Detached breakwaters and breakwaters attached to jetties are constructed parallel to shore to serve as a shore protection measure. The planform response of the shoreline to the placement of a breakwater must be considered in the design process. The response can take the form of a tombolo that extends from shore to attach to the structure, a salient or cusp in the shoreline that extends partially to the structure, or a null response. Herbich (1999) reviews available empirical and numerical predictive capabilities for the functional design of detached breakwaters.

Hanson and Kraus (1989, 1990) identified 14 parameters controlling beach response to detached breakwaters. They performed extensive numerical simulations over a wide parameter range, validated by reference to performance of structures in the field, to produce the following predictive expression for beaches with 0.2 mm median grain size:

$$\frac{X}{L} \le N(1 - K_t)\frac{H_0}{D} \tag{1}$$

where X = length of breakwater, L = wavelength at the breakwater located in depth D, K_t = wave transmission coefficient, H_0 = deepwater wave height, and N = empirically determined coefficient distinguishing response of the beach to the structure. Their work demonstrated that wave transmission is a leading parameter determining shoreline response. It is not reliable to apply an

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14. ABSTRACT
Wave transmission is a leading parameter determining the response of the shoreline to a detached breakwater, reef, or spur attached to a jetty. To improve the predictive capability of the shoreline response numerical model GENESIS, published empirical formulas for the wave transmission coefficient were incorporated to calculate time-dependent wave transmission and shoreline response. Simulations for different structural configurations, wave climates, and water levels demonstrate the functional utility of time-dependent wave transmission on shoreline response predictions. Results indicate that variable wave transmission is of significance for modeling the response of the beach to submerged and emergent near-surface structures. Predictions of the model are examined in application to a functional design of a submerged spur being studied as a possible sediment-control measure for the north jetty at Grays Harbor, WA. Results show that for design applications, beach response under time-varying forcing cannot be anticipated with a constant transmission coefficient. The improved capability is expected to have wide applicability.

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empirical criterion to beaches where grain size, tidal range, and wave conditions differ from those underlying the criterion. Numerical models are recommended for application in general situations of arbitrary structure configurations, time-varying water level and waves, and different median grain size.

Numerical models typically represent wave transmission as a constant K_t specific to each detached breakwater. However, wave transmission properties vary over different time scales as controlled by tidal variations and incident wave conditions. The purpose of this study is to improve predictive modeling capability by incorporating an automated time-dependent calculation of wave transmission and shoreline response. The functioning of the variable K_t for various structure configurations is demonstrated by comparing the shoreline response predictions of simulations based upon time-dependant and constant values of K_t.

GENESIS IMPLEMENTATION

Wave transmission properties of a structure can vary significantly depending on structure configuration and composition. Wave transmission properties also vary over different time scales as controlled by tidal variations and the changes in incident waves. It is desirable to have the capability of predicting shoreline response to detached breakwaters for a wide range of engineering conditions. To achieve this goal, an expression for the wave transmission coefficient must be valid over a broad range of environmental forcing and breakwater designs. Wamsley and Ahrens (2003) critically evaluated several empirical predictive formulas for wave transmission at detached breakwaters, leading to an approach judged most appropriate for shoreline response modeling.

The functioning of the time-dependent K_t is assessed by incorporating the predictive formulas in the numerical model GENESIS. GENESIS has been applied to model shoreline change both in the field and in movable-bed physical model experiments based on its capability of representing combined wave diffraction, refraction, and transmission at multiple detached breakwaters (e.g., Hanson and Kraus 1989, 1990, 1991a, 1991b). In GENESIS, wave transformation from deep water to the location of the structure may be calculated by selecting either an external 2-D wave transformation model, e.g., STWAVE (Smith et al. 1999), or the internal wave module within GENESIS. In these previous works, the transmitted wave was calculated with a constant value of K_t as discussed, for example, by Hanson et al. (1989) and Hanson and Kraus (1991a). Through an iterative procedure for calculating wave breaking, K_t also influences the breaking wave height and direction alongshore, thereby determining the associated shoreline response to the structure (Hanson and Kraus 1989, 1990, 1991a, 1991b).

In the revised GENESIS model as described here, the user may choose either a constant value of K_t for each structure or allow the model to calculate values based on time-varying water level and wave height, and structure characteristics. Based on the input values describing the structure, water level, and calculated wave properties, a corresponding K_t is calculated at each time step. The calculated K_t exerts strong influence on the wave field behind and adjacent to the structure because it contributes to wave transmission and diffraction. If the variable K_t option is selected, water level is read from an input file at a specified input time interval. For each structure, the user specifies geometric properties (crest height and width, slopes on seaward and landward sides, and median rock size) and can select between the calculation methods of Ahrens (2001); Seabrook and Hall (1998); and d'Angremond et al. (1996). Wamsley and Ahrens (2003) provide guidance on selecting a calculation method for a given application.

ANALYSIS

The functional utility of the variable K_t for various structural configurations and wave climates is demonstrated by comparing the shoreline response predictions of simulations based upon time-dependent and constant values of K_t. Simulations were performed for a (1) single submerged, (2) emergent near-surface, and (3) high breakwater at an initially straight shoreline. The high breakwater was designed such that there was little or no wave overtopping, and wave energy was only transmitted through the structure. Simulations for each structure were forced with both a typical Atlantic and Gulf of Mexico wave climate. Wamsley and Ahrens (2003) found that the dominant mode approach (Ahrens 2001) to calculating wave transmission was most appropriate for application over a wide range of conditions and this method was used for the following analysis. Simulations were first run with variable transmission and the average K_t computed by the Ahrens formula was assigned for the constant K_t simulations. The magnitude of the shoreline change for each calculation method is a function of several factors including wave climate, water levels, sand grain size, depth of active transport, etc. and will differ depending on the application and the calibration of the model. The percent difference between the constant and time-dependent wave transmission shoreline predictions indicates the utility of the time-dependent calculation.

Submerged Structure

Figure 1 shows calculated shoreline position change behind a 300-m long submerged detached breakwater located 300 m offshore for both a typical Atlantic and Gulf of Mexico wave climate after a simulation time of 4 years. The crest of the structure is at elevation –2 m mean sea level (msl). The seaward extent of the salient is much greater for the variable K_t simulation. The average shoreline change behind the structure is 70% greater for the Atlantic wave climate and 90% greater for the Gulf wave climate. The difference owes to the sensitivity of the prediction to water level and incident wave height. For submerged structures, the dominant mode of wave transmission is over the crest and the larger the wave, the less efficient the transmission process. Figure 2 plots change in K_t versus wave height at constant water level for the Atlantic wave climate and is representative of the Gulf of Mexico results. The variable K_t computation reduces the larger waves and increases the smaller waves relative to the constant K_t simulation. Because longshore transport is proportional to wave height H as $H^{5/2}$, a change in higher waves produces greater change in transport than does a similar height differential for smaller waves. The result is greater shoreline advance behind the structure for the variable K_t simulation.
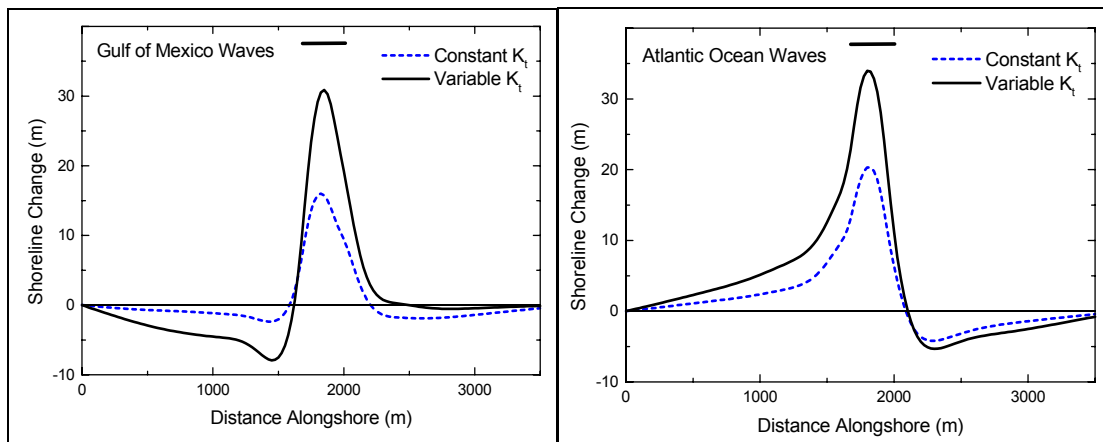

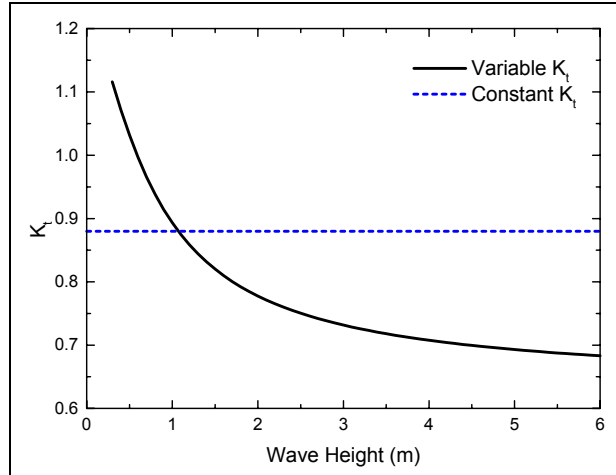Fig. 1. Shoreline change behind a submerged breakwater

Fig. 2. Change in K_t versus wave height at a constant water level for a submerged structure

The shoreline change as illustrated in Figure 1 and the difference between the constant and variable K_t simulations represents the change at a particular moment in time. To assess the role of variable wave transmission in simulations, the relative difference must be examined over time. Figure 3 plots the percent difference between the constant and variable K_t simulation predictions of shoreline change for the Atlantic wave climate by month for a 1-year interval. The application of the variable K_t results in a 40-80% difference in the predicted average shoreline change behind the structure. A similar difference in shoreline response to a structure with constant and variable wave transmission was found for the Gulf of Mexico wave climate.
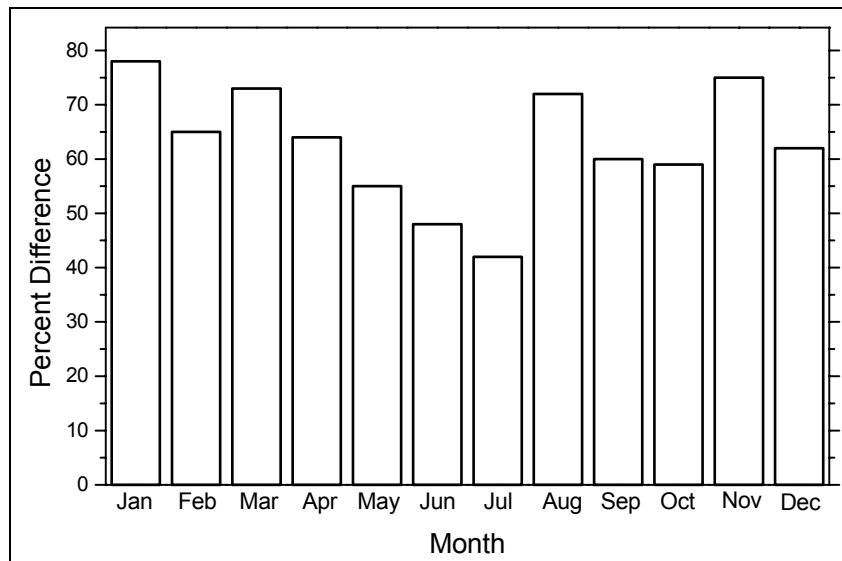

Fig. 3. Percent difference in shoreline change behind submerged structure between constant and time-dependent K_t calculation methods, by month

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Emergent Near-Surface Structure

Figure 4 shows the 4-year shoreline position change behind a 300-m long detached breakwater located 300 m offshore for the Atlantic and Gulf wave climates described above. The crest of the structure is at elevation +1 m msl. The variable transmission simulation predicts less shoreline change behind the structure for both wave climates. Figure 5 plots change in K_t versus wave height at constant water level for the Atlantic wave climate and is representative of the Gulf of Mexico results. The variable K_t results in less shoreline change because, for rubble mound breakwaters with a crest located just above the still-water level, the dominant mode of wave transmission is by runup and overtopping, and the efficiency of the transmission process increases as the wave height increases. Thus, the variable K_t computation increases the height of the larger waves and reduces the smaller waves relative to the constant K_t simulation. The result is less shoreline advance behind the structure for the variable K_t simulation.
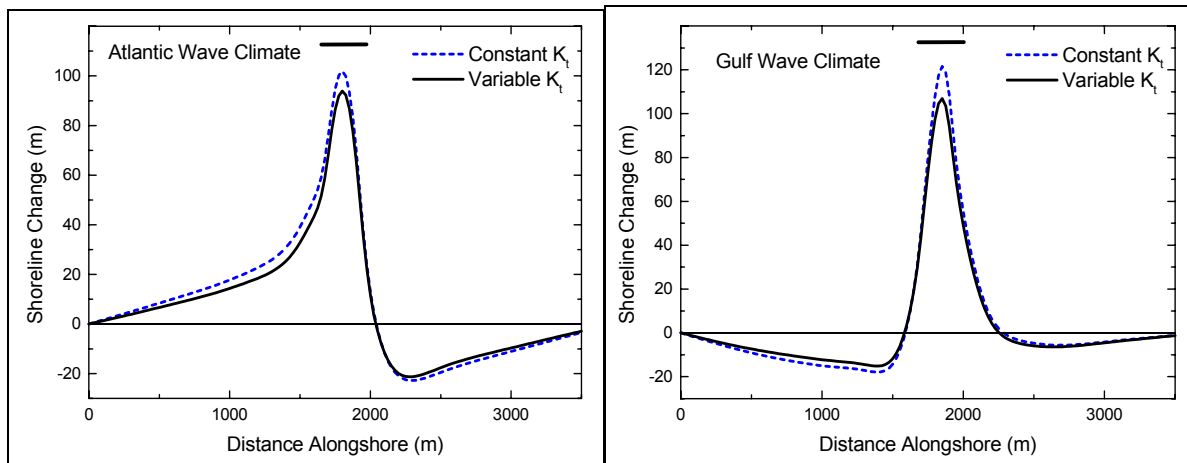

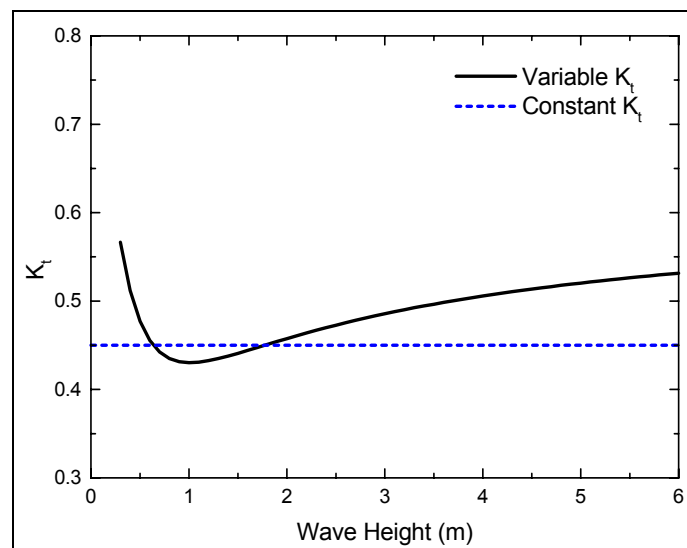Fig. 4. Shoreline change behind an emergent near-surface breakwater

Fig. 5. Change in K_t versus wave height at constant water level for emergent near-surface structure

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The increase in K_t for waves less than about 1 m in height is caused by wave transmission through the structure. For small waves, the dominant mode of wave transmission is through the structure. If the scale of disturbance is large compared to the void spaces in the stone, the transmission process is inefficient. As the wave height becomes smaller, the transmission process is more efficient and produces larger values of K_t. However, the relatively small waves do not create significant changes in the shoreline position.

Figure 6 plots the percent difference between the constant and variable K_t simulation predictions for the Atlantic wave climate by month for a 1-year interval. The results are representative of the Gulf of Mexico wave climate. The application of the variable K_t results in 10-30% less average shoreline advance behind the structure. Therefore, shoreline planform predictions can be significantly different in applying a time-dependent wave transmission and are expected to be more accurate than if applying a constant value of K_t or omitting wave transmission altogether.
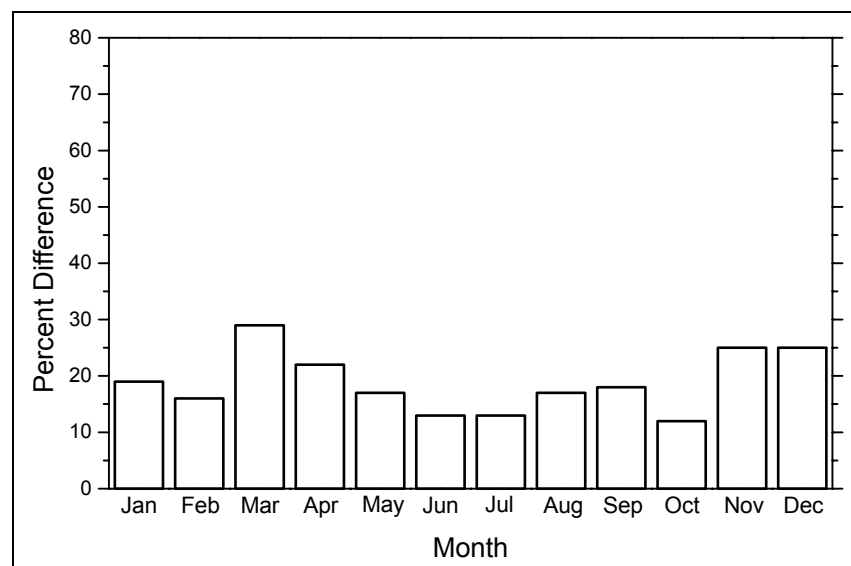

Fig. 6. Percent difference in shoreline change behind emergent near- surface structure between constant and time-dependent K_t calculation methods by month

Emergent High Structure

Figure 7 shows the 4-year shoreline position change behind a 300-m long detached breakwater located 300 m offshore for both wave climates. The crest of the structure is at elevation +6 m msl. The average shoreline change behind the structure predicted by the variable K_t simulation is less than 5% greater than the constant K_t simulation for both wave climates.

Figure 8 plots the percent difference between the constant and variable K_t simulation shoreline change predictions for the Atlantic wave climate by month for a one-year period. The application of the variable K_t results in no more than a 5% difference in the predicted average shoreline change behind the structure. Results are similar for the Gulf of Mexico wave conditions. The high crown elevation allows wave transmission only through the breakwater, and changes in water level have no effect. The average K_t for both wave climates is about 0.2. Transmitted waves are small, and any difference between constant and variable K_t computations is small resulting in relatively little difference in shoreline change.
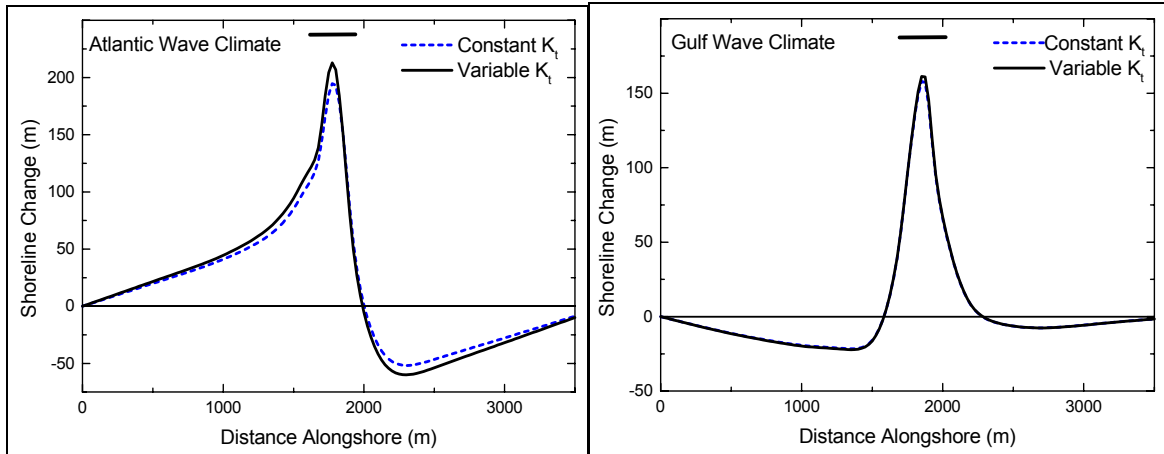
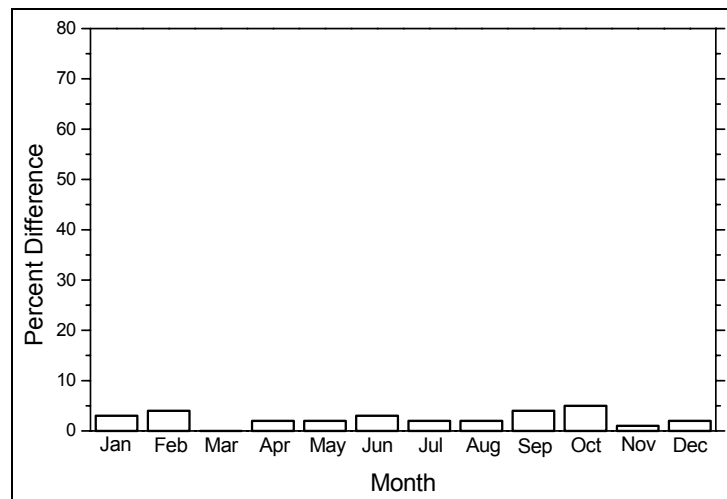Fig. 7. Shoreline change behind emergent high breakwater

Fig. 8. Percent difference in shoreline change behind emergent
high structure between constant and time-dependent K_t
calculation methods, by month

CASE STUDY – GRAYS HARBOR, WA

Predictions of the model for submerged structures was further examined in application to a functional design of a submerged spur being studied as a possible sediment-control measure for the north jetty at Grays Harbor, WA (Figure 9). Grays Harbor, located on the Pacific Ocean coast of the USA, is one of the largest estuaries in the continental United States. The tide is semi-diurnal with 2- to 3-m neap to spring typical range. The adjacent beaches have a slope of approximately 1 on 60 and median sand grain size of 0.25 mm. A high-energy wave climate produces average annual significant wave heights of 2 m and peak periods of 10 s. However, winter storms generate waves greater than 6 m high and 17-s period.

The entrance to Grays Harbor is bounded on both sides by rubble mound jetties. The north jetty was constructed to block southward transport of sediment and to protect and maintain the entrance navigation channel (USACE 1973). The effectiveness of the north jetty has decreased because of subsidence and deterioration, resulting in sediment being transported into the inlet, potentially

increasing the need for maintenance dredging. The beach north of the jetty has recently exhibited a tendency to erode, reversing a historic trend of advancement. Construction of a submerged spur off the north jetty has been proposed as a potential alternative for trapping and retaining sand and for promoting a morphological response that will protect the jetty from scour. The proposed spur is 450 m long and will be placed at a water depth of approximately 8 m msl. It is a reef-type rubble mound structure with a median rock size of 0.9 m. Initially considered spur dimensions are crest height of 3.6 m, crest width of 10 m, seaward facing slope of 0.2, and a landward facing slope of 0.3.

Fig. 9. Grays Harbor site map

GENESIS Application

The GENESIS model was calibrated for the proposed Grays Harbor project site (Wamsley and Hanson 2002). The model was driven by a representative time series developed from the offshore wave record from a deepwater buoy deployed off Grays Harbor. Nearshore reference waves input to GENESIS were computed with STWAVE, and the internal wave model in GENESIS calculated the breaking wave parameters. The spur was modeled as a detached breakwater in GENESIS. The time-varying water level file required for computing the transmission coefficient was created by input of local tide data taken in this study. The year 2000 shoreline served as the initial shoreline, and a 4-year simulation was run by selecting the Ahrens transmission formulation. A 4-year simulation with constant K_t was also run to assess the significance of varying K_t with the waves and water level. The average $K_t = 0.87$ computed by the Ahrens formula for the 4-year record was assigned for the constant-K_t simulation.

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The predicted shorelines, together with the 4-year simulated shoreline without the spur, are plotted in Figure 10. The difference in the calculated shoreline planforms demonstrates the leading role of the variable K_t computation. The variable K_t formulation produces four times more shoreline advance (more than 60 m) behind the spur than predicted with a constant K_t. The primary reason for the difference is again the sensitivity of the prediction to water level and incident wave height. The change in K_t versus wave height for constant water level is similar in form to that in Figure 2.

The directionality of the wave climate also plays a role. The Grays Harbor wave climate is characterized by higher winter waves that approach from the west-southwest and drive sand to the north, in contrast to the more prevalent smaller summer waves that approach from the west-northwest and drive sand to the south. The large winter waves tend to erode the beach near the jetty as they transport sediment northward with no immediate supply possible through bypassing at the inlet. Waves from the west-northwest transport sand toward the inlet where it is impounded at the jetty and widens the beach or bypasses the jetty and enters the inlet. The reduced wave heights predicted by the variable K_t for the large waves reduces the removal of sand and promotes increased accretion behind the spur. The U.S. Army Engineer District, Seattle is completing a feasibility study of the spur that includes these results.
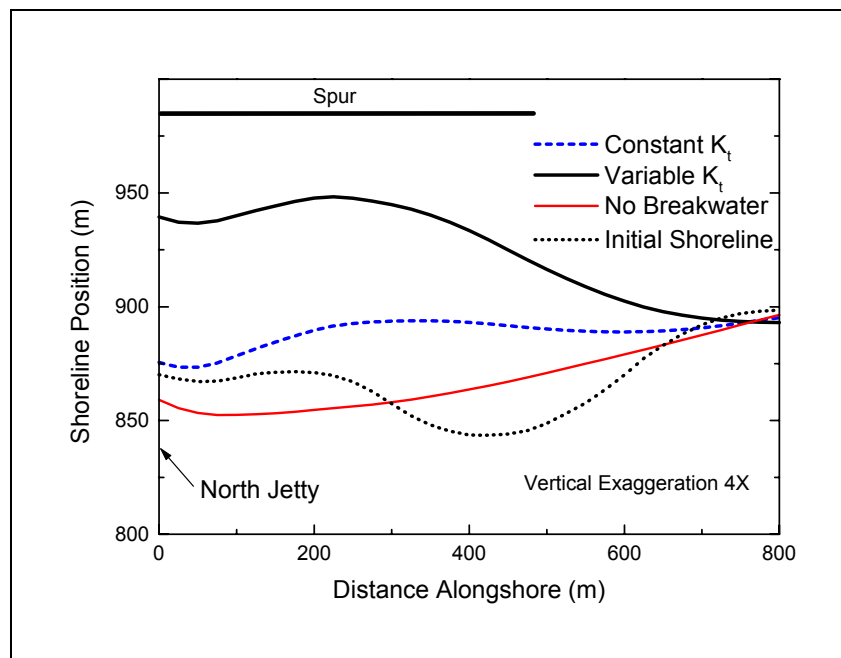

Fig. 10. Predicted shoreline, Grays Harbor WA

CONCLUSIONS

Wave transmission at a detached breakwater is a leading parameter among many variables controlling the response of the shoreline to the structure. Wave transmission depends on the configuration and composition of the structure, wave height and period, and water depth, and the forcing parameters are time dependent. Empirical formulas for predicting the response of the shoreline to detached breakwaters can only crudely account for wave transmission at locations where the tidal range and wave height, period, and direction vary.

Numerical models have the capability of representing the response of the shoreline to structures exposed to time-varying forcing. In this study, published empirical formulas for the wave transmission coefficient were incorporated in the GENESIS shoreline change model to calculate time-dependent wave transmission and shoreline response. The functional utility of time-dependent wave transmission was assessed running simulations for a single detached breakwater of varying crest heights and forced with a range of wave conditions. Results indicate that the time-dependent K_t enters centrally for all wave climates and plays a major role for submerged and emergent near-surface structures. The application of a time-dependent wave transmission calculation entered most significantly for submerged structures, for which shoreline position predictions may change by 80% or more. The time-dependent calculation appears to be necessary to represent emergent near-surface structures because application of a constant K_t may over-predict shoreline advance by as much as 30%. These percentages apply to the wave climates and structural configurations tested. Greater changes may be possible for a given application as illustrated by the Grays Harbor case study.

The functional utility of time-dependent wave transmission was further examined in application to a submerged spur being studied as a possible sediment-control measure for the north jetty at Grays Harbor, WA. Predicted shoreline response to a proposed submerged shore-parallel spur on the north jetty differed considerably between the constant and the time-dependent wave transmission cases. Sensitivity tests indicated that seasonal directionality and energy of the incident waves, combined with the variable wave transmission, contributed to a significant difference in predictions. The combined working of wave direction and wave transmission demonstrates the complex interaction of forcing parameters that cannot be anticipated by a constant transmission coefficient for design applications.

Predictive capability of numerical shoreline response models such as GENESIS can be improved by incorporating a time-dependant wave transmission calculation for detached breakwaters. In the present study, K_t is represented in a more realistic manner than previously, and results indicate that the time-dependant nature of wave transmission is a major factor in determining shoreline response for submerged and emergent near-surface structures. In practice, detached breakwaters are often submerged to reduce cost, produce moderate shoreline change, and to minimize dangerous diffraction currents. Therefore, the improved simulation capability in GENESIS is expected to have wide applicability.

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